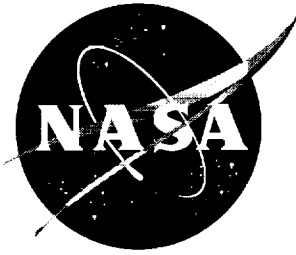


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Fluid Mechanics, Drag Reduction and Advanced Configuration Aeronautics

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December 2000

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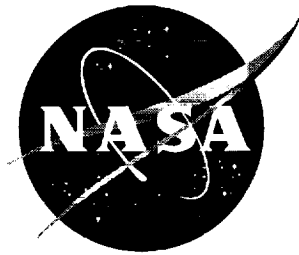
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Dennis M. Bushnell

Abstract

Paper discusses Advanced Aircraft configurational approaches, across the speed range, which are either enabled, or greatly enhanced, by clever Flow Control. Configurations considered include Channel Wings with circulation control for VTOL [but non-hovering] operation with high cruise speed, strut-braced CTOL transports with wing-tip engines and extensive ["natural"] laminar flow control, a midwing double fuselage CTOL approach utilizing several synergistic methods for drag-due-to-lift reduction, a supersonic strut-braced configuration with order of twice the L/D of current approaches and a very advanced, highly engine flow-path-integrated hypersonic cruise machine. Paper indicates both the promise of synergistic flow control approaches as enablers for "Revolutions" in aircraft performance and fluid mechanic "areas of ignorance" which impede their realization and provide "target-rich" opportunities for Fluids Research.

Introduction

This paper speaks to perhaps THE major reason for the extraordinary level and longevity of [Governmental and Industrial] institutional support for Aeronautical research in Fluid Mechanics and its technological handmaiden--Flow Control. This rationale is, of course, the expectation [or at least the hope] of major SYSTEM performance improvements. Alone among transportation modes the overall viability of flying vehicles is exquisitely sensitive to levels of both lift and drag--quantities which are, in detail and essence, nothing more nor less than derivatives of Applied Fluid Mechanics [aka Aerodynamics].

Over the nearly 100 years of powered human flight, Fluid Mechanics Research has sometimes led but often lagged Aeronautical Engineering Concepts and Practices. As always, "Real Machines" are a SYSTEM-WIDE summation of mutual compromises over many disciplines, of which fluid mechanics is among [but only among] the major "players," along with propulsion efficiency [wherein fluids also plays a major role], structural efficiency, stability and control, life cycle costs, safety, etc. Therefore, while a particular new[er] approach or concept or increase in "understanding" on the fluids side may be viewed by the fluids community as a major step

forward, any real importance in the aero engineering sense only emerges when the work is folded into the overall system aspect[s] (ref. 1). A classic object lesson in this regard is laminar flow control, which to this point has enjoyed some 60 years of serious and careful research including MANY extensive and usually successful flight campaigns. This technology, while wonderfully successful from a fluids perspective and capable of providing MAJOR “fluids” gains, has not as yet been employed other than passively [“by design”] on small aircraft --due to systems cost issues (ref. 2). A perhaps useful general rule-of-thumb is that any proffered fluids-enabled “gain”/benefit should be as large as possible to ensure that, after all the system trades and losses/“puts and takes” some reasonable residue of favorable advantage still remains. For many reasons, as concepts mature toward real systems the usual result is reduced performance/weight gain etc.

In point of fact, Fluid Mechanics has not been particularly productive in the aero overall systems sense for decades. Almost all of the considerable improvements in aircraft performance since the early 70’s were due to propulsion advances, primarily higher bypass ratio. As an example, the lift-to-drag ratio of transport aircraft has been nearly moribund since the early 60’s (ref. 3). This has led to initially rumblings and more recently increasingly strident calls that aircraft aero/fluid dynamics is a “mature field,” a “sunset endeavor”--there is not much left to gain except by the glacial accretion of a percent here and there [and often less] over long time periods. Fluid mechanics IS trying to contribute in a substantial way to improvements in “design cycle.” This activity is often quite distinct from performance enhancement per se although improved “tools” will enable the efficient evaluation of alternative configurations/concepts. We have obviously nearly achieved an “optimum” in CTOL aircraft design. The fundamental thesis of this paper is that this optimum is merely a LOCAL, not a GLOBAL optimum. If alternative overall vehicle configurations and missions are examined, many of which have SYNERGISTIC concomitant improvements in other discipline areas [by “design”] there appear to be tremendous opportunities for major aero performance benefits **ENABLED BY FLUID MECHANICS** and Flow Control. This article will attempt to briefly describe several such situations and opportunities, as an indication of both potential future promise of fluids contributions in the aero systems arena and as perhaps fertile areas for fluids research studies.

“Designer Fluid Mechanics”

The advanced configurations discussed herein utilize and indeed are enabled by “flow control in the large,” sometimes termed “Designer Fluid Mechanics.” This is a set of technologies, and fundamentally a mindset, developed over the last 60 years+, which essentially “unhooks” the flow both locally and globally from the local physical body coordinates. Subdisciplines within this topical approach include laminar flow control [drag reduction], mixing enhancement [noise, combustion], separated flow control [high lift, drag reduction], vortex control [separation control/maneuverability, vortex hazard], turbulence control [drag reduction, mixing], circulation control [high lift], anti-noise, favorable wave interference [drag reduction] and even “designer fluids.” These areas have been studied primarily, thus far, as individual entities as opposed to synergistically in the context of an overall design. In many cases individual flow control approaches have been taken to the flight test stage and beyond, with several actually entering service. These latter include blown flaps on some 50’s era fighters, a large number and variety of “vortex generators” for separation control, “variable geometry” of various persuasions, “natural” laminar flow, [supersonic] passive inlet bleed, jet injection thrust vector control in rockets, transition trips and, increasingly, active noise cancellation. Several other approaches look exceedingly favorable from the fluids viewpoint [e.g., they “work”] but thus far systems considerations have not favored major applications. These include circulation control [provides up to a factor of 4 increase in lift, much of this with no “moving parts”], suction laminar flow control, riblets, jet vortex generators, porous surface shock mitigation and a host of others. In general and thus far, “successful”/ deployed flow control approaches are characterized by being simple/inexpensive, passive, retrofittable, reliable/foolproof, fully simulatable in ground facilities, and very well characterized and understood [along with providing unique/nontrivial system enhancement] (ref. 1).

The Channel Wing

The channel wing is an example of an advanced configuration which was somewhat ahead of its time. The concept was originally developed, essentially empirically, in the 40’s and early 50’s as a STOL light aircraft and several versions were flown, this is not just a “paper airplane.” The essential technology consists of a semicircular airfoil “channel” underneath, and surrounding on the underside, “standoff” wing mounted engine nacelles such that the engine-induced airflow produces sizable lift on the wing “channel” at zero-to-low forward speed, providing dramatic STOL capability. Measurements of pounds of lift-per-horsepower are in the helicopter range. The developers of the configuration claimed, but there was never any satisfactory “proof,” perhaps due to “then year” control problems, that the

approach was capable of near VTOL performance. Development of this concept has been essentially dormant since the late 50's except for Soviet research. Antonov produced an advanced prototype-demonstrator in the late 80's termed the AN 181 (ref. 4).

The original 40's-to-50's era research on the channel wing was, by necessity, highly empirical and resource constrained (see references 5-12). The concept provides a classic example of an approach worth revisiting with updated tools and technology to ascertain the extent to which its STOL performance could approach VTOL. In particular, the incorporation of circulation control in the classical sense (via blowing immediately upstream and above the trailing edge), when combined with the engine-induced flow over the wing, should further augment the lifting capability of the configuration. Also, a serious attempt should be made to reduce the requisite propulsive mass flow currently and historically required for circulation control (via "dynamic flow control"). Additional technology updates/approaches of possible interest include (power on) CFD (so the approach could be "designed" instead of "engineered"), flow separation avoidance and control, wing laminar flow for cruise performance and inboard strut bracing along with the all important vehicle controls issues.

The potential for such an updated channel wing approach to address the commercial and military "V-22 niche" should be determined as the channel wing could possibly incorporate very interesting lifting capabilities with a fairly high cruise speed at reduced weight/cost compared to the V-22 (with its engine rotation requirements and associated systems penalties).

CTOL Transport with Strut/Truss-Braced Wings and Wing-Tip Engines

Pfenninger has long advocated strut bracing to improve the performance of conventional transports (refs. 13-20). The resulting (bending, torsion) structural benefits allow reduced wing thickness, weight, leading edge diameter and sweep resulting in a tremendously enhanced and easily maintained (reduced sensitivity to roughness/insect remains/ice clouds, reduced cross flow) extent of natural-to-easily forced low drag laminar flow, as well as increased span. The latter allowed a reduction in wing chord, further enhancing the extent of laminar flow, as well as enhanced takeoff and climb performance and reduced vortex hazard. Pfenninger's designs for such aircraft yielded L/D values in the 40's, over twice current levels. The concept was not, however, adopted primarily because the extensive wing span did not fit the FAA "80 meter box" for airport gate compatibility and disbelief that a transonic strut braced wing could be designed with acceptable shock drag (and obtain laminar flow on the strut/truss). Obviously strut-bracing is

routinely employed on low(er) speed aircraft. The latter objection is probably not valid in light of today's CFD capabilities.

The span of a strut braced configuration can probably be reduced to the 80 meter requirement and the overall performance retained if an alternative approach is employed for major drag-due-to-lift reduction-wing tip engine placement (also enabled by strut/truss bracing). Whitcomb (ref. 21) and others (refs. 22-30) have shown that up to the order of 50 percent DDL reductions are obtainable using this approach, which probably requires circulation control on the empennage region (powered by the APU) and utilization of thrust vectoring on all engines to handle the "engine out" problem. The Pfenninger approach of wing sweep/thickness reductions and consequent natural-to-easily forced wing laminar flow as enabled by strut bracing is also retained.

The use of tip engines for aerodynamic drag-due-to-lift and wake vortex reduction is part of an overall paradigm shift in aircraft design wherein a configurational concept is sought in the context of an "open thermodynamic system," i.e., synergistic use is made of the energy added by the propulsion system. Historically, aerodynamic theory is almost totally predicated upon analysis within a "closed system" (no energy added within the control volume). By necessity, as speed is increased, increasing use has been made of favorable propulsive interactions--wing propulsive pre compression/engine nacelle favorable interference lift at supersonic speeds and, at hypersonic conditions, the entire undersurface of the body is an integral part of the engine flow path for the airbreather case. However, little "first principles" work is available regarding favorable propulsive interactions in the subsonic case.

A theoretical construct for aerodynamic optimization in an open system is not yet extant, but there are several discrete examples, in addition to the wing-tip engine case, where synergistic airframe/ aerodynamic propulsion integration has been studied and in some cases even applied. These include circulation control wing flow which offers up to a factor of 4 increase in CL compared to conventional flaps and slats with tremendous reductions in "part count" (ref. 31), wake/boundary layer ingestion into the propulsion system [order of 15 percent increase in propulsion efficiency (ref. 32)] including synergistic interaction with an LFC suction system (ref. 33); thrust vectoring for control (e.g., X-31, "tail-less fighters, etc.) and, hypersonically, for lift enhancement and thrust requirement reduction; utilization of a leading edge region LFC suction system for high lift during takeoff; the ejector wing for improved structural and aero efficiency (ref. 34); wing tip injection for wake vortex and drag-due-to-lift reduction and myriad propulsive-augmented high lift schemes. An additional major opportunity for synergistic propulsion aerodynamic interaction is the "Goldschmied" wing (or body), a takeoff on the Griffith wing (ref. 35). The basic concept is to position the propulsive

inlet in the recompression region on the wing/afterbody to effectively place "sinks" inside the body and convert much of the balance of the afterbody into a stagnation region instead of having a rear stagnation "point." Estimates indicate up to a 50 percent "cancellation" of the body friction drag is possible via this "static pressure thrust" approach (refs. 36-40).

Double Fuselage

Conventionally, double fuselage/multi-body aircraft have been employed to provide span-load distribution and accrue the associated structural weight benefits (reduced wing bending moment) without going all the way to a "blended wing body"/spanloader configuration i.e., providing such benefits via more "comfortable" "conventional" technology. Total aircraft drag is also reduced, primarily due to favorable effects on drag-due to-lift (refs. 41-45).

An advanced double fuselage approach (ref. 46) could attempt to delete the conventional outer wing panels and only retain a, largely unswept/long chord, wing section between the fuselages. This requires prodigious drag due-to-lift reduction, a requirement which can be addressed via design of the fuselages as wing-tip "end plates" and the individual fuselage empennage as "winglets," i.e., the tails become thrusting surfaces in the presence of the wing vorticity wrapping around the fuselage(s) and engines "buried" at the rear of the fuselages to accrue the benefits of "boundary layer ingestion" as well as drag due to lift reduction (engines buried in the rear of the fuselage(s) on this configuration now become "wing tip engines" as the fuselages are located at the wing tips).

For this case, the "midwing" can become the site of the gear (to allow use of conventional runways) and extensive (natural/ suction) laminar flow. A major payoff would accrue from making the fuselages detachable/interchangeable to provide a civilian "sky-train" with enhanced productivity. The midwing portion which does all the "flying" could be in the air nearly "around the clock" with freighter and/or passenger modules, thereby nearly doubling the productivity/duty cycle and "return on investment." Such an approach would allow a restructuring of the airline capital investment, with the airlines "owning" their fuselages and leasing midwing time from a "rent-a-wing" company. Obviously, military versions could have cargo, troop, and refueling fuselages--providing a quantum jump in military flexibility and productivity.

Strut-Braced Extreme Arrow SST Configuration

Supersonic Transports will always be at a disadvantage with respect to their subsonic brethren due to shock wave drag--their forte is speed, not efficiency. While CTOL transports have a modicum of "compressibility" or wave drag [alleviated by sweep, decreased wing thickness etc.], they operate "by design" either just below or at the knee of the drag rise curve to ensure that the wave drag level is "tolerable." The drag breakdown for an SST on the other hand is nominally 1/3 each of friction, vortex drag-due-to-lift and wave drag, the latter composed of both wave drag-due-to-lift and volume wave drag. The current advanced state of the art SST machines have an L/D level in the neighborhood of 9, greater than the nominal [1950's] Concorde level of 7+ but still not enough to meet the very stringent SST economic metrics which probably require something in the range of 12 or greater (ref. 47). Pfenninger, on the basis of synergistic flow control approaches, proffered an interesting and challenging design with an L/D value in the high teens (refs. 48, 49). The essential concept was to utilize external strut bracing to allow practical realization of the "extreme arrow" planform. This shape minimizes wave drag due to lift, increases aspect ratio and reduces wetted area and wing chord, thereby reducing wing Reynolds number and enhancing the payoff of suction laminar flow control. Laminar flow control also increases (overland flight) subsonic cruise efficiency (necessitated by sonic boom proscriptions). Another perhaps viable drag reduction approach is slot (wall wake) turbulent skin friction reduction via injection of LFC suction (and inlet bleed) air. Mid-wing fuel tanks were utilized for both load alleviation and to provide favorable shock wave interference/volume wave drag reduction. This latter probably necessitates utilization of separation control at cruise in the regions of shock-boundary layer interaction (ref. 47). Natural laminar flow control would be utilized/"designed into" both the mid-wing tanks and the fuselage nose region, using "fuel cooling," especially on the tanks, to enhance the transition delay of the favorable pressure gradients on these essentially 2-D [axisymmetric] bodies.

Such an SST configurational approach would change completely the economics of the beast, as, far more than in the subsonic case, these machines are "flying fuel tanks" with a mere 1% drag reduction providing the order of a 15 Klb reduction in takeoff weight. Along with L/D another key design constraint for this vehicle class/mission is takeoff noise reduction. A particularly interesting, and to this point essentially virgin approach is to "stage" the vehicle by injecting liquid water drops into the causative supersonic shear layers to both change the noise transmission characteristics AND disable the noise sources themselves. That water drops can reduce noise significantly is agreed, there are many deployed terrestrial systems, the issue is whether, through careful [probably experimental] and clever fluids

research the amount of water required could be reduced significantly. The extensive parameter space includes droplet mean size[s], size distribution[s], injection location[s]/orifice size[s], injection velocity vector[s], and surfactant[s] as well as tailoring of the supersonic shear layers to be more “receptive” to the water treatment. Also this approach INCREASES THRUST whereas other proffered noise reduction schemes, many studied at great time and expense, reduce thrust. Finally, the water is used up upon takeoff, the tank is jettisoned and there is little-to-no system weight that must be carried throughout the flight.

Efficient Hypersonic In-Atmospheric Cruise

From a civilian perspective Hypersonic in-atmospheric cruise makes most sense, economically, in terms of a “Fed-Ex” package delivery capability in the Mach Number range from 4 to 6. The prime route would be transpacific. The “market pull” comes from the ongoing economic development of the “Pacific Rim.” Military applications of this class of capability include “Global Reach” strike and reconnaissance. From both an economic and a vehicle performance perspective the “fuel of choice” would be endothermic hydrocarbons where the fuel is “cracked” within the engine cooling system to provide additional heat sink capability. This choice utilizes the conventional/“storable” airport fuels infrastructure/destination matrix and allows a compact, RELATIVELY inexpensive vehicle design. Such “fuel cooling” would also be highly efficacious for “conventional” gas turbine engines by providing cycle regeneration benefits while simultaneously reducing cooling air bleed and injection losses. The propulsion cycle of choice is a Ramjet [at cruise] in this Mach Number Range, perhaps of the “deeply cooled” Air-Turbo variety (ref. 50). The prime overall design precept for such a machine is the necessity of extreme propulsion/airframe integration with the vehicle undersurface serving as both external inlet and nozzle.

Fluid Mechanics will of necessity play an enabling function for this class of vehicle in terms of combined aero/propulsive performance and control[s]. Starting with leading edge bluntness, this should be simultaneously optimized for wave drag reduction [minimum wave drag is finite bluntness], heating reduction and transition delay. Also, a “spatula,” as opposed to an axisymmetric nose region delays forebody transition appreciably. A critical arena where fluids research/invention could have a major impact is in the internal inlet leading into the combustor. Current practice utilizes an “isolator,” essentially a physical inlet extension [with associated large performance penalties in terms of weight, heating etc.] to minimize separated flow effects upon inlet operability. At lower speeds passive bleed is used instead of an isolator but heat transfer precludes use of bleed in most hypersonic applications. What is needed is invention/development of “bleedless/isolatorless” inlet boundary layer

separation control treatments. A somewhat interesting possibility in this regard is the use of [TBD] 3-D surface “bumps” which both create weak shock trains which amplify the boundary layer turbulence/delay separation and engender smaller/3-D separated flow regions which are less disruptive. Within the combustor LOW LOSS fuel mixing and penetration enhancement would enable greatly improved engine weights/costs and increased overall engine flowpath performance. Such mixing enhancement may be available via identification and excitation of discrete instabilities still present in, and overlaying, the usual shear flow turbulence dynamics.

It is in the nozzle area where fluid mechanics can make the largest contribution to overall viability (ref. 51). A basic issue is vehicle trim/controllability and the trim drag associated with conventional control surfaces is a major performance hit. In addition, and SYNERGISTICALLY, at hypersonic speeds major benefits accrue from use of “thrust vectoring” for lift at cruise—reduces wave drag due to lift, angle of attack, heat transfer, wetted area, skin friction, weight, and overall total thrust requirement by as much as order of 20%. Therefore [particularly external nozzle] Flow Control for thrust vectoring for both vehicle control and lift [at these very demanding conditions] is a potentially interesting, and important, fluids research arena.

Concluding Remarks

This discussion and exploration of advanced configuration Aeronautics, as enabled by flow control and multi-disciplinary synergisms, indicates/suggests the following areas of potentially useful fluids research:

1. Approaches, perhaps via mixing control and profile tailoring, to reduce the mass flow injection requirements for circulation control .

2. Approaches, perhaps via non-planer surfaces, for “bleedless” supersonic and “isolatorless” hypersonic inlets.

3. [Systems-compatible] flow separation control AT CRUISE to allow exploitation of “inviscid” optimizations [e.g. for favorable shock wave interference for wave drag reduction ,increased leading edge thrust, enhanced upper surface lift].

4. Development of the capability to COMPUTE in a DESIGN sense aerodynamics in an open thermodynamic system, i.e. in the presence of propulsion energy/mass flow addition. Essentially all of the known Aero optimizations are in the context of a closed thermodynamic system. There exist several specific examples of very favorable airframe/propulsion integration possibilities [e.g. wing tip engines, Goldschmied wing/body closure, circulation control etc.] and the entire parameter space should be explored to discover what other aero/propulsive synergisms might be possibly interesting.

5. Modeling techniques for supersonic two-phase flows for application to SST noise reduction.

6. Capability to PREDICT flight performance on and off design [for safety considerations] for advanced configurations. This necessarily includes aeroelastic distortions, correct transition locus, correct Reynolds number scaling, propulsion system/integration effects, trim and roughness. This is needed to allow effective/efficient evaluation of different/ strange/ wondrous concepts. A major reason we keep building the “same old stuff” is that we have data and experience on “the same old stuff.” Our scaling capability is very modest. We can “predict,” based upon extensive previous experience, what will happen. We cannot predict ab initio and therefore are loath to “take the risk on a wholly new design. We thus as a technical community often pretend that other opportunities are not available when they are. In fact quite a few of them with many more to be conceived/discovered.

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13. ABSTRACT (Maximum 200 words) Paper discusses Advanced Aircraft configurational approaches, across the speed range, which are either enabled, or greatly enhanced, by clever Flow Control. Configurations considered include Channel Wings with circulation control for VTOL [but non-hovering] operation with high cruise speed, strut-braced CTOL transports with wing-tip engines and extensive ["natural"] laminar flow control, a midwing double fuselage CTOL approach utilizing several synergistic methods for drag-due-to-lift reduction, a supersonic strut-braced configuration with order of twice the L/D of current approaches and a very advanced, highly engine flow-path-integrated hypersonic cruise machine. Paper indicates both the promise of synergistic flow control approaches as enablers for "Revolutions" in aircraft performance and fluid mechanic "areas of ignorance" which impede their realization and provide "target-rich" opportunities for Fluids Research.				
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